Advanced Electromagnetics:
21st Century Electromagnetics

Frequency Selective Surfaces & Metasurfaces

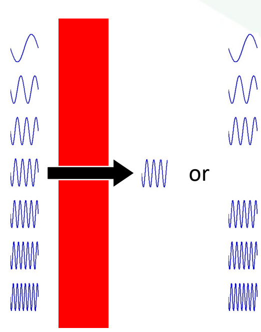
Lecture Outline

- Introduction
- Simple examples
- Grating lobes
- Classifications and comparisons
- All-dielectric frequency selective surfaces
- Metasurfaces
- Conclusions

Introduction

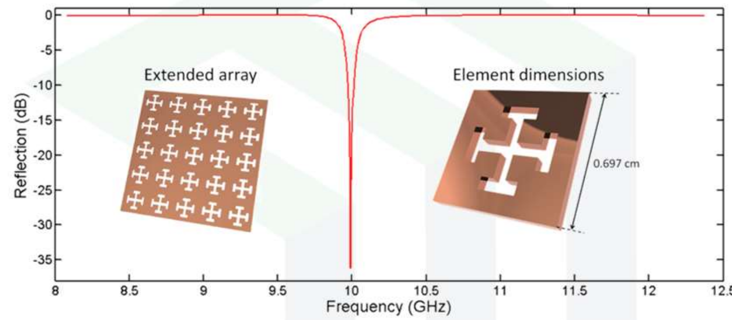
Definition of Frequency Selective Surface

A frequency selective surface is composite material designed to be transparent in some frequency bands while reflective, absorbing or redirecting to others. They are typically flat and composed of metal screen.

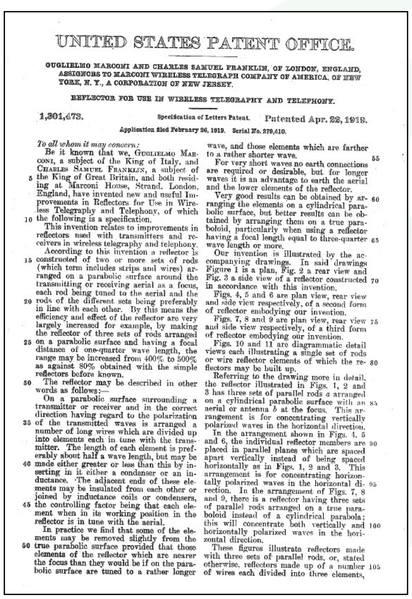


EMPossible

Examples



The First Radio Frequency FSS



UNITED STATES PATENT OFFICE.

GUGLIELMO MARCONI AND CHARLES SAMUEL FRANKLIN, OF LONDON, ENGLAND, ASSIGNORS TO MARCONI WIRELESS TELEGRAPH COMPANY OF AMERICA, OF NEW YORK, N. Y., A CORPORATION OF NEW JERSEY.

REFLECTOR FOR USE IN WIRELESS TELEGRAPHY AND TELEPHONY.

1,301,473. Specification of Letters Patent. Patented Apr. 22, 1919.

Application filed February 26, 1919. Serial No. 279,410.

To all whom it may concern:

Be it known that we, GUGLIELMO MARCONI, a subject of the King of Italy, and CHARLES SAMUEL FRANKLIN, a subject of the King of Great Britain, and both residing at Marconi House, Strand, London, England, have invented new and useful Improvements in Reflectors for Use in Wireless Telegraphy and Telephony, of which the following is a specification.

This invention relates to improvements in reflectors used with transmitters and receivers in wireless telegraphy and telephony.

According to this invention a reflector is constructed of two or more sets of rods (which term includes strips and wires) arranged on a parabolic surface around the transmitting or receiving aerial as a focus, each rod being tuned to the aerial and the rods of the different sets being preferably in line with each other. By this means the efficiency and effect of the reflector are very largely increased for example, by making the reflector of three sets of rods arranged on a parabolic surface and having a focal distance of one-quarter wave length, the range may be increased from 400% to 500% as against 80% obtained with the simple reflectors before known.

The reflector may be described in other words as follows:—

On a parabolic surface surrounding a transmitter or receiver and in the correct direction having regard to the polarization of the transmitted waves is arranged a number of long wires which are divided up into elements each in tune with the transmitter. The length of each element is preferably about half a wave length, but may be made either greater or less than this by inserting in it either a condenser or an inductance. The adjacent ends of these elements may be insulated from each other or joined by inductance coils or condensers, the controlling factor being that each element when in its working position in the reflector is in tune with the aerial.

In practice we find that some of the elements may be removed slightly from the true parabolic surface provided that those elements of the reflector which are nearer the focus than they would be if on the parabolic surface are tuned to a rather longer wave, and those elements which are farther to a rather shorter wave.

For very short waves no earth connections are required or desirable, but for longer waves it is an advantage to earth the aerial and the lower elements of the reflector.

Very good results can be obtained by arranging the elements on a cylindrical parabolic surface, but better results can be obtained by arranging them on a true paraboloid, particularly when using a reflector having a focal length equal to three-quarter wave length or more.

Our invention is illustrated by the accompanying drawings. In said drawings Figure 1 is a plan, Fig. 2 a rear view and Fig. 3 a side view of a reflector constructed in accordance with this invention.

Figs. 4, 5 and 6 are plan view, rear view and side view respectively, of a second form of reflector embodying our invention.

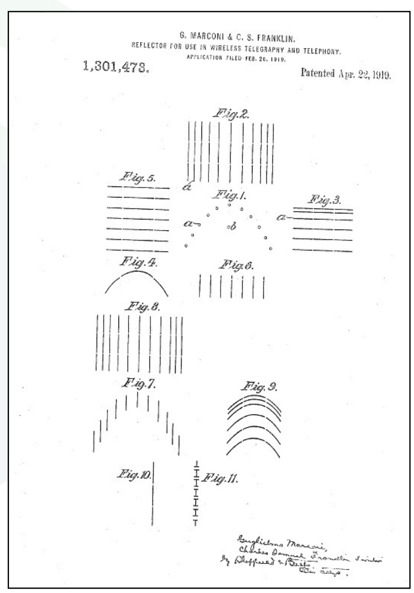
Figs. 7, 8 and 9 are plan view, rear view and side view respectively, of a third form of reflector embodying our invention.

Figs. 10 and 11 are diagrammatic detail views each illustrating a single set of rods or wire reflector elements of which the reflectors may be built up.

Referring to the drawing more in detail, the reflector illustrated in Figs. 1, 2 and 3 has three sets of parallel rods *a* arranged on a cylindrical parabolic surface with an aerial or antenna *b* at the focus. This arrangement is for concentrating vertically polarized waves in the horizontal direction.

In the arrangement shown in Figs. 4, 5 and 6, the individual reflector members are placed in parallel planes which are spaced apart vertically instead of being spaced horizontally as in Figs. 1, 2 and 3. This arrangement is for concentrating horizontally polarized waves in the horizontal direction. In the arrangement of Figs. 7, 8 and 9, there is a reflector having three sets of parallel rods arranged on a true paraboloid instead of a cylindrical parabola; this will concentrate both vertically and horizontally polarized waves in the horizontal direction.

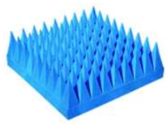
These figures illustrate reflectors made with three sets of parallel rods, or, stated otherwise, reflectors made up of a number of wires each divided into three elements,

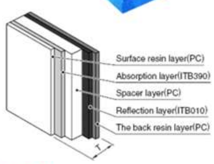


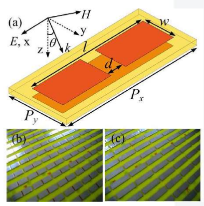
Physical Mechanisms for Frequency Selectivity

FREQUENCY SELECTIVE SURFACE
To perform frequency selectivity (filtering), power must be absorbed and/or redirected.

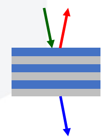
ABSORPTION
Devices are made absorptive by incorporating lossy materials. The absorption can be amplified by also incorporating resonant structures.

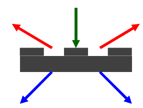


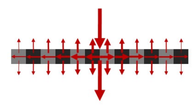




REDIRECTION
Power is redirected using interference and diffraction. This can be simple reflection, diffraction from a grating or through a guided-mode resonance.







EMPossible

Slide 7

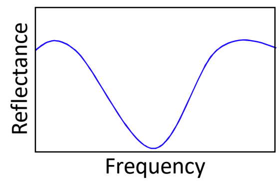
Some Simple Examples

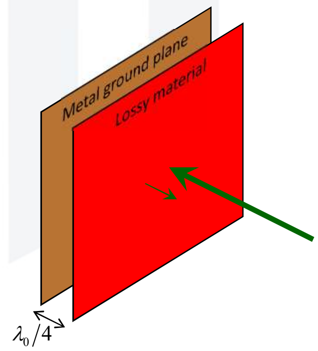
Slide 8

Salisbury Screen

A Salisbury screen was one of the first concepts for frequency selective surfaces and was used by the military to make military vehicles "invisible" to radar.

At the frequency in which the device is resonant, energy is absorbed in the lossy material.

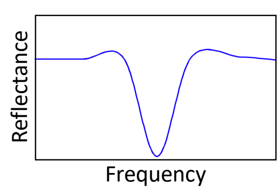


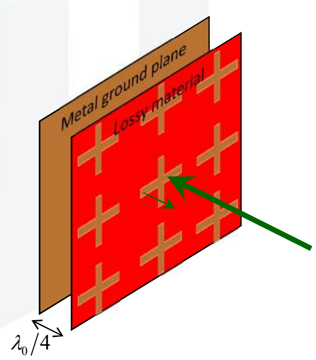


Circuit Analog Absorber

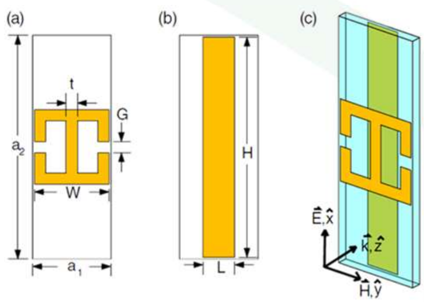
A circuit analog absorber is like a Salisbury screen, but it incorporates periodic structures that amplify the absorption by enhancing the resonance.

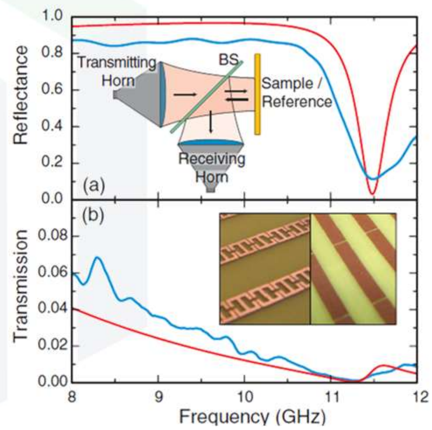
Can provide sharper or more tailored resonances





"Perfect" Metamaterial Absorbers

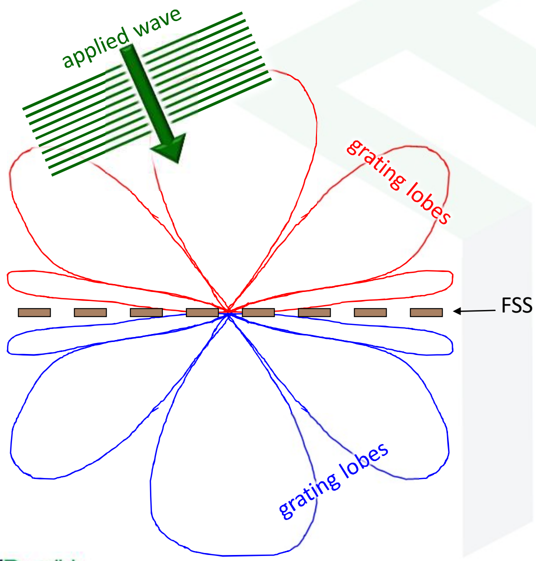




N. Landy et al, "Perfect Metamaterial Absorber," Phys. Rev. Lett. **100**, 207402 (2008).

Grating Lobes

Definition of Grating Lobes



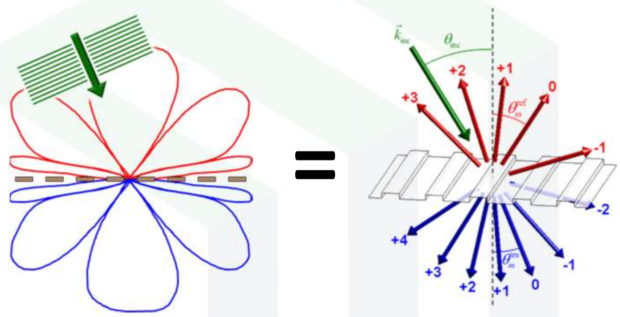
Frequency selective surfaces are diffraction gratings and will diffract an applied wave into discrete directions if the frequency is high enough.

This is usually seen as a bad thing.

RF engineers call these grating lobes or specular reflection. Optical engineers call these diffraction orders. The are "lobes" due to the bandwidth of the signal.

Grating lobes are a far-field concept. It does not make sense to think about grating lobes within a device.

Grating Lobe Condition



Grating Lobe Condition (Grating Equation)

$$k_0 n \sin\theta_m = k_0 n_{\text{inc}} \sin\theta_{\text{inc}} - \frac{2\pi m}{\Lambda_x}$$

$$n \sin\theta_m = n_{\text{inc}} \sin\theta_{\text{inc}} - m\frac{\lambda_0}{\Lambda_x}$$

$n \equiv$ refractive index around diffracted order
$n_{\text{inc}} \equiv$ refractive index around applied wave
$\Lambda_x \equiv$ interelement spacing (grating period)
$m = \cdots, -2, -1, 0, 1, 2, \cdots$

Onset of Grating Lobes

Although grating lobes can provide a redirection mechanism for frequency selectivity, they are typically viewed as a bad thing.

It is usually desired to operate FSSs at frequencies below a cutoff where there are no grating lobes (no diffracted modes).

Assuming the FSS is operated in air ($n = n_{\text{inc}} = 1.0$), this cutoff condition (onset of grating lobes) occurs when $\theta_{\pm 1}$=90°:

$$f_{\text{c}} = \frac{c_0}{\Lambda_x \left(\sin\theta_{\text{inc}} - 1 \right)}$$

$$\lambda_{0,\text{c}} = \Lambda_x \left(\sin\theta_{\text{inc}} - 1 \right)$$

EMPossible

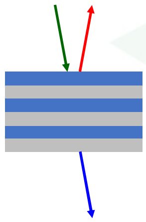
15

Classifications and Comparisons

Slide 16

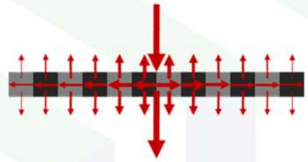
Redirection Mechanisms

Longitudinal Resonance



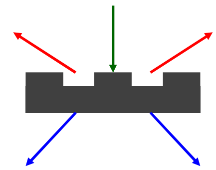
A beam is incident from the top and partially reflects from each of the surfaces. It is the overall interference of the scattered waves that produces the frequency selectivity.

Transverse Resonance



An external wave is coupled into a guided mode or surface wave. The guided-mode slowly leaks from the guide due to the grating. It is the interference between the applied wave and the "leaked" wave that produces the frequency selectivity.

Diffractive



An applied wave is incident on a grating that scatters it into multiple directions. Frequency selectivity is produced by the inherent frequency dependence of scattering from a grating.

Multilayer Vs. Single Layer FSS

A tremendous amount of control over the shape of the response of a FSS can be realized using multilayer resonant structures. This approach can combine absorption, longitudinal resonance, transverse resonance and diffraction into a single device.

Multilayer structures are generally more sensitive to angle of incidence.

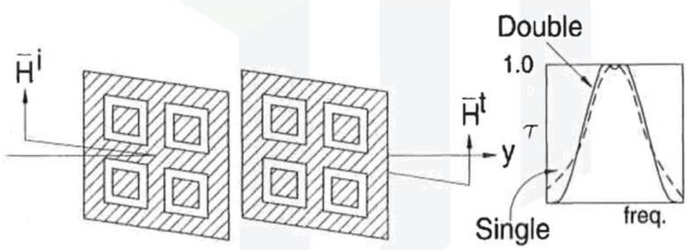
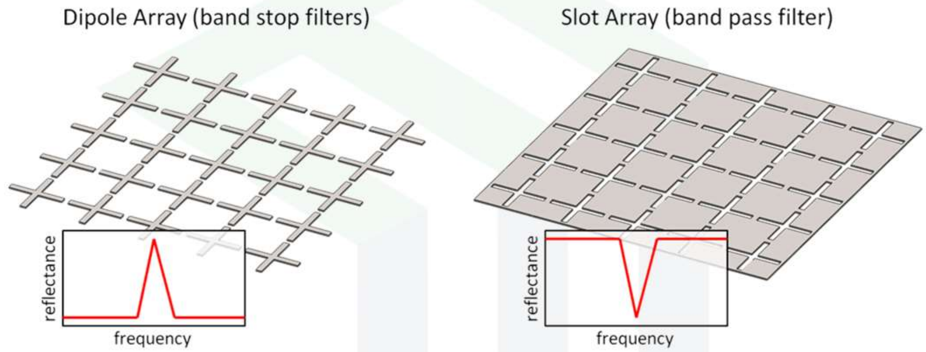


FIGURE 1.7. By using cascaded *periodic structures* we can obtain a broader top and faster roll-off. However, the bandwidth will vary considerably with angle of incidence.

Dipole Array Vs. Slot Array



The above structures are also called "complementary" arrays because they are exact inverses of each other. According to *Babinet's principle for complementary surfaces*, their frequency responses will also be exact inverses of each other. In practice, this is not the case because the metals are not perfectly conducting and not infinitely thin. Further, if dielectric is incorporated, these structures can behave very differently.

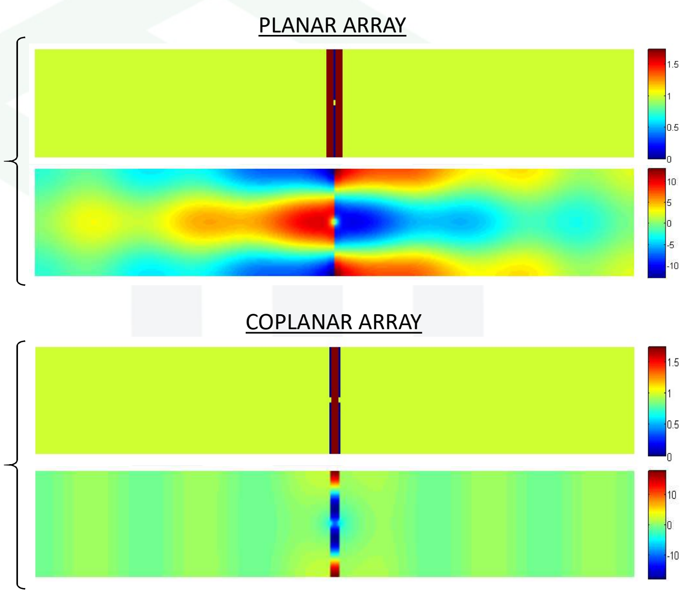
Tan, Zhong Ming, and Kirk T. McDonald. "Babinet's Principle for Electromagnetic Fields."

EMPossible

Planar Vs. Coplanar Arrays

Dielectric-Metal-Dielectric
- Large evanescent field
- Less sensitive to dielectric
- More sensitive to external environment

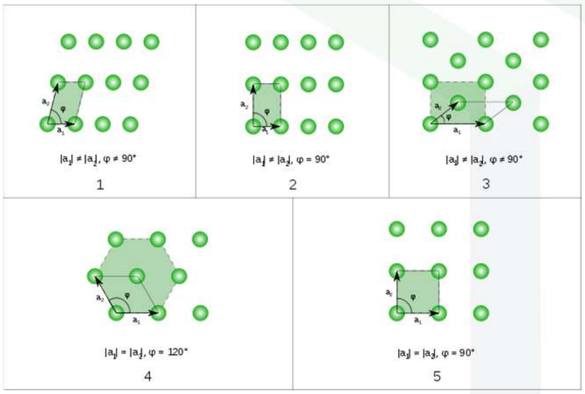
Metal-Dielectric-Metal
- Evanescent field confined between plates
- Greater sensitivity to dielectric
- Less sensitivity to external environment



EMPossible

Array Symmetry Considerations

Frequency selective surfaces are essentially planar devices so only consider the five 2D Bravais lattices have to be considered.



For a given element shape, the hexagonal array can fit more elements per unit area than any other symmetry.

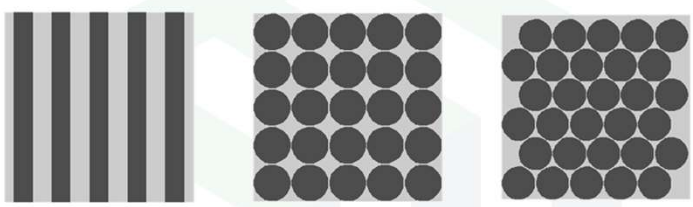
Hexagonal arrays have higher "packing density."

Equivalently, the element size can be larger relative to the lattice spacing in a hexagonal array.

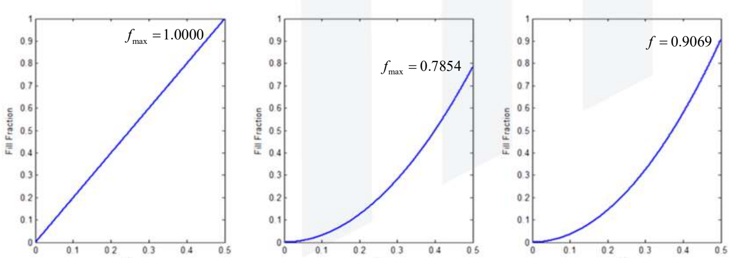
The onset of grating lobes tends to be farther out for hexagonal arrays so they are most desirable from this perspective.

Modeling and manufacturing hexagonal arrays can be more difficult.

Fill Fraction Comparison



$$f = 2\left(\frac{r}{a}\right) \qquad f = \pi\left(\frac{r}{a}\right)^2 \qquad f = \frac{2\pi}{\sqrt{3}}\left(\frac{r}{a}\right)^2$$



Hexagonal array provides 15.4% higher fill factor.

Common Element Types

LP polarizer

Can be packed tight.
Broadband.

Small size relative to λ.
Very broadband.

Isolated resonances
Best for narrowband

Reflecting and
transmitting
Very broadband
Small element

$L \sim \frac{\lambda_0}{2}$

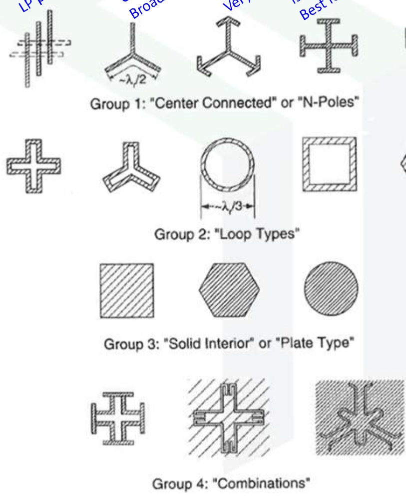
Secondary resonances problematic.
Larger elements relative to wavelength.

$c \sim \lambda_0$

Small relative to wavelength.
Circumference is ~λ.
Common band-pass element.
BW control through line thickness.

$L \sim \frac{\lambda_0}{2}$

Earliest and simplest elements studied.
Large relative to wavelength.
Angle sensitive.
Grating lobes a problem.



Munk, Ben A. *Frequency selective surfaces: theory and design*. John Wiley & Sons, 2005.

EMPossible

All-Dielectric Frequency Selective Surfaces

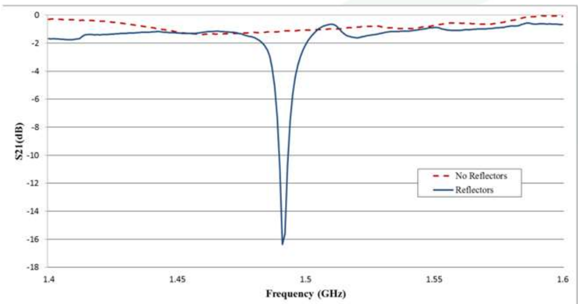
Why All-Dielectric?

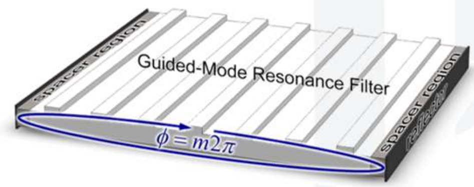
- Metals can be lossy (especially at optical frequencies)
- Structure may need to be low observable (LO)
- Can be handled more safely in high-voltage environments
- Maybe better suited for high power
- Can be monolithic

Dielectric Mechanisms for Frequency Selectivity

- Stacks of layers
  - Great for optics, but bulky at radio and microwave frequencies
- Naturally absorbing materials
  - May be best approach if it is possible
- Diffraction gratings
- Guided-mode resonance
  - Limited bandwidth
  - Limited field-of-view
  - Typically required to be 100’s of periods

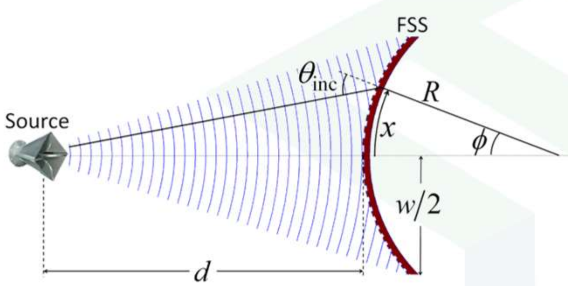
All-Dielectric FSS with Few Periods

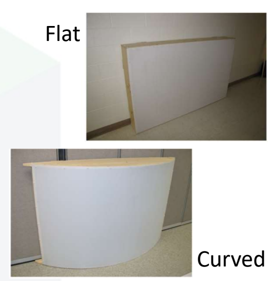




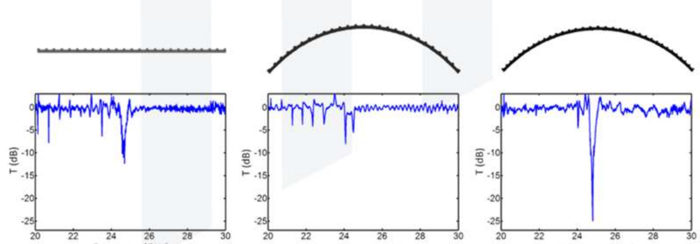
Jay H. Barton, R. C. Rumpf, R. W. Smith, "All-Dielectric Frequency Selective Surfaces with Few Periods," PIERS B, Vol. 41, pp. 269-283, 2012.

All-Dielectric FSS on Curved Surface





R. C. Rumpf, M. Gates, C. L. Kozikowski, W. A. Davis, "Guided-Mode Resonance Filter Compensated to Operate on a Curved Surface," PIER C, Vol. 40, pp. 93-103, 2013.

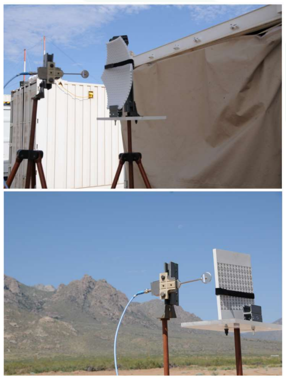


(a) Uncompensated flat design. (b) Uncompensated curved FSS (c) Compensated curved FSS

All-Dielectric Frequency Selective Surfaces

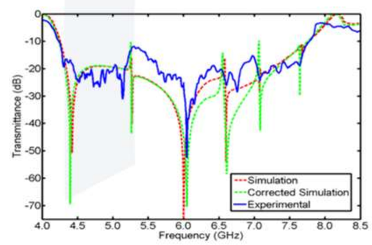
Highest Power FSS

Operated at over 2.0 GW!



J. H. Barton, C. R. Garcia, E. A. Berry, R. G. May, D. T. Gray, R. C. Rumpf, "All-Dielectric Frequency Selective Surface for High Power Microwaves," IEEE Transactions on Antennas and Propagation, 2014.

Most Broadband All-Dielectric FSS



J. H. Barton, C. R. Garcia, E. A. Berry, R. Salas, R. C. Rumpf, "3D Printed All–Dielectric Frequency Selective Surface with Large Bandwidth and Field-of-View," IEEE Trans. Antennas and Propagation, Vol. 63, No. 3, pp. 1032-1039, 2015.

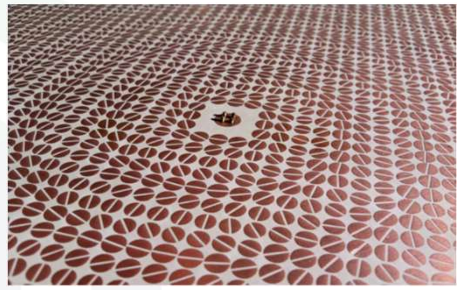
EMPossible

Slide 29

Metasurfaces

Slide 30

Definition



http://www.innoget.com/O.3072/Method-for-designing-a-modulable-metasurface-antenna-structure

Metasurfaces are essentially planar nonresonant metamaterials.

Ingredients for a definition:

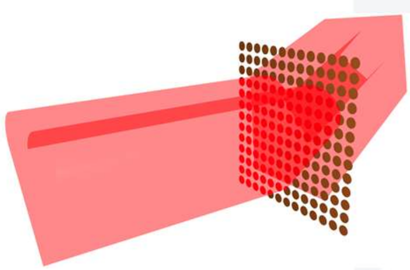
- Subwavelength thickness
- Flat composite structure
- Engineered electromagnetic properties
- Affects waves through modified boundary conditions instead of effective properties

EMPossible 31

Metasurfaces Vs. Metamaterials

Metamaterials – function is to realize artificial μ and ε.

Metasurfaces – function is to modify wave fronts arbitrarily.

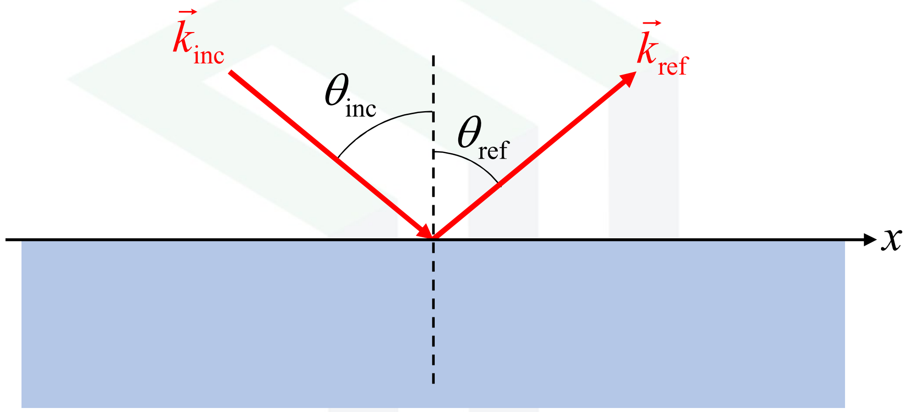


Metasurfaces can arbitrarily control the following as a function of position:

- Amplitude
- Polarization
- Phase
- Angles (i.e. phase)
- Frequency (nonlinear)
- Reciprocity (nonlinear, anisotropic, etc.)

EMPossible 32

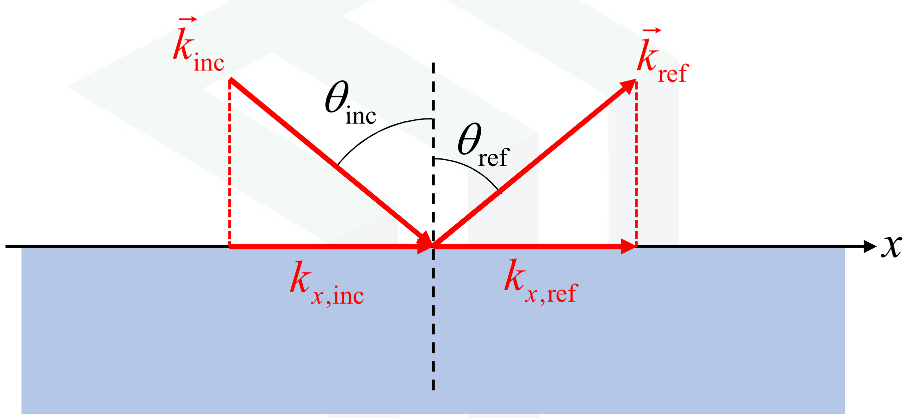
Standard Law of Reflection



$$\boxed{\theta_{\text{ref}} = \theta_{\text{inc}}}$$

33

How Does Phase Accumulate Across Surface?

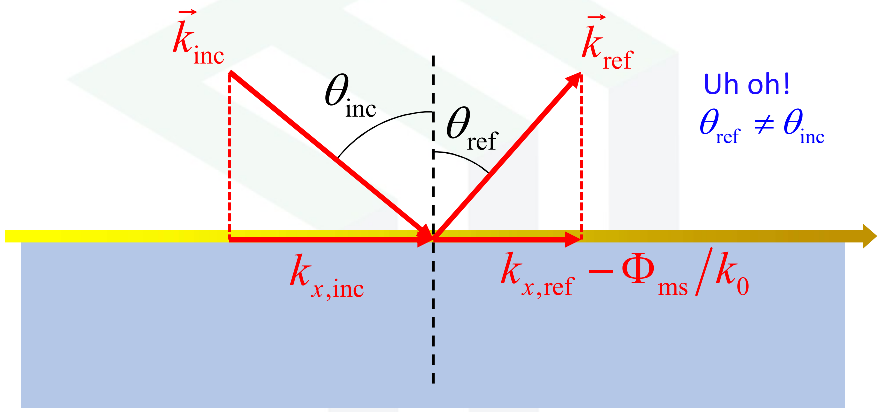


$$\phi_{\text{inc}}(x) = k_{x,\text{inc}} x \qquad \phi_{\text{ref}}(x) = k_{x,\text{ref}} x$$

$$\frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}} \qquad \frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}}$$

34

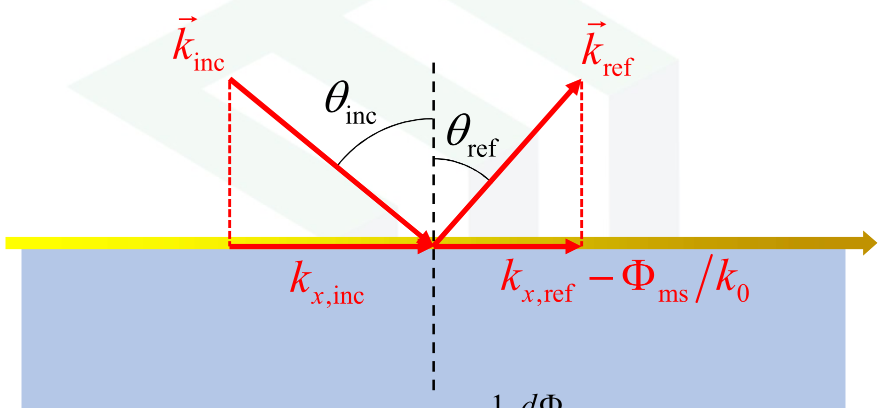
What if the Surface Affected Phase?



$$\phi_{\text{inc}}(x) = k_{x,\text{inc}}x \qquad \phi_{\text{ref}}(x) = k_{x,\text{ref}}x - \Phi_{\text{ms}}/k_0$$

$$\frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}} \qquad \frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}} - \frac{1}{k_0}\frac{d\Phi_{\text{ms}}}{dx}$$

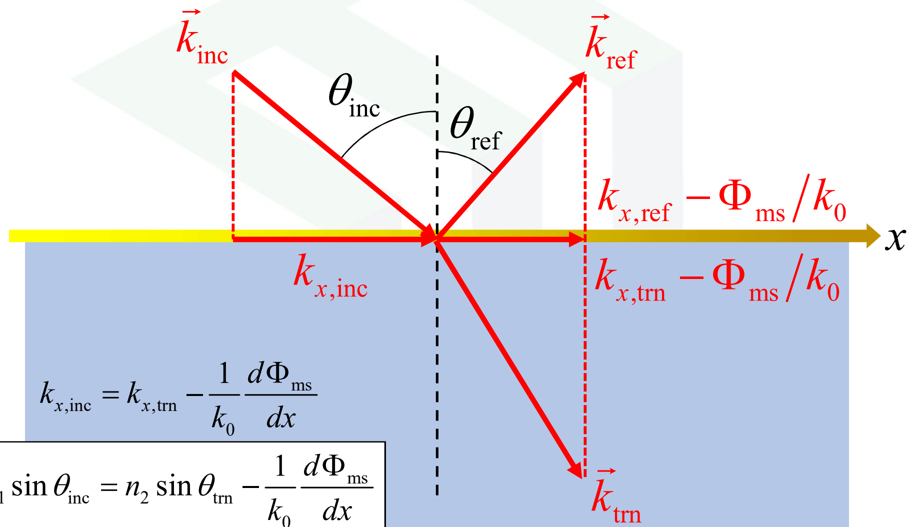
Modified Law of Reflection



$$k_{x,\text{inc}} = k_{x,\text{ref}} - \frac{1}{k_0}\frac{d\Phi_{\text{ms}}}{dx}$$

$$\boxed{n_1 \sin\theta_{\text{inc}} = n_1 \sin\theta_{\text{ref}} - \frac{1}{k_0}\frac{d\Phi_{\text{ms}}}{dx}}$$

Modified Law of Refraction

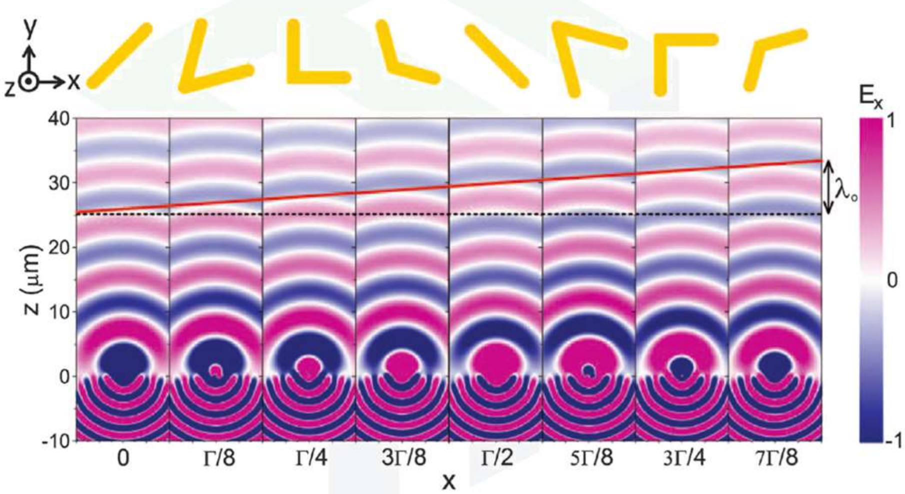


$$k_{x,\text{inc}} = k_{x,\text{trn}} - \frac{1}{k_0}\frac{d\Phi_{\text{ms}}}{dx}$$

$$\boxed{n_1 \sin\theta_{\text{inc}} = n_2 \sin\theta_{\text{trn}} - \frac{1}{k_0}\frac{d\Phi_{\text{ms}}}{dx}}$$

EMPossible 37

A Famous Metasurface Element (1 of 2)

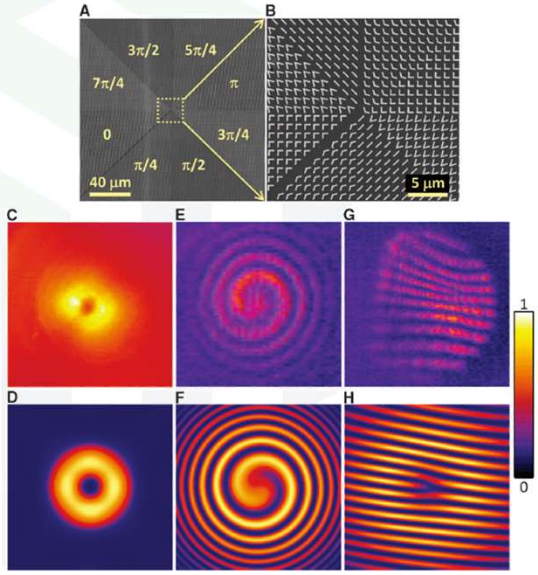


Yu, Nanfang, et al. "Light propagation with phase discontinuities: generalized laws of reflection and refraction." science 334.6054 (2011): 333-337.

EMPossible 38

A Famous Metasurface Element (2 of 2)

Fig. 5. (**A**) SEM image of a plasmonic interface that creates an optical vortex. The plasmonic pattern consists of eight regions, each occupied by one constituent antenna of the eight-element set of Fig. 2F. The antennas are arranged so as to generate a phase shift that varies azimuthally from 0 to 2π, thus producing a helicoidal scattered wavefront. (**B**) Zoom-in view of the center part of (A). (**C** and **D**) Respectively, measured and calculated far-field intensity distributions of an optical vortex with topological charge one. The constant background in (C) is due to the thermal radiation. (**E** and **F**) Respectively, measured and calculated spiral patterns created by the interference of the vortex beam and a co-propagating Gaussian beam. (**G** and **H**) Respectively, measured and calculated interference patterns with a dislocated fringe created by the interference of the vortex beam and a Gaussian beam when the two are tilted with respect to each other. The circular border of the interference pattern in (G) arises from the finite aperture of the beam splitter used to combine the vortex and the Gaussian beams (*20*). The size of (C) and (D) is 60 mm by 60 mm, and that of (E) to (H) is 30 mm by 30 mm.



Yu, Nanfang, et al. "Light propagation with phase discontinuities: generalized laws of reflection and refraction." science 334.6054 (2011): 333-337.

EMPossible

Conclusions

Conclusions About FSSs

- Typically want small and tightly packed elements
  - Broadband
  - Robust to angle of incidence
  - Grating lobes less problematic
- The resonant frequency and bandwidth usually depends mostly on the element shape and size, not the array spacing or symmetry.
- The frequency where grating lobes are present depends only on the element spacing and angle of incidence, not the element type (remember FSSs are gratings)
- All-dielectric FSS are an option for niche applications.

Conclusions About Metasurfaces

- Elements are much more subwavelength than with FSSs
- Elements control wave fronts
  - Amplitude
  - Polarization
  - Phase
  - Angles
  - Frequency
  - Reciprocity